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The Effects of Energy Consumption on The Turning Process For Various Work-Piece Materials

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Abstract

The study modified its goal to energy-intensive titanium alloys, contrasting traditional and high-speed machining processes. According to the study, a solution is needed to reduce or optimize energy use. So, a machined component energy footprint model was created. Several cutting speeds were used to calculate (k). Material removal rates were compared to cutting speeds for a range of materials and levels of detail. A strategy for selecting optimal cutting conditions was then created and tested. An optimal tool life equation that meets the most minor energy conditions was constructed. From this, each material's specific energy was determined. Machinability is the ease with which a material can be cut while maintaining a high standard of tool life and finished product quality. Most electricity went to non-cutting processes. Most energy goes to the spindle, control computer, and cooling fans. Non-cutting tasks require the most power on a CNC lathe. Cutting used 13 to 36% of the machining energy for various workpiece materials. When comparing the required energy for various technological alloys for a given volume of product removal, machining at a higher speed or with a greater volumetric removal rate results in lower energy usage. Energy requirements are also affected by the nature of the material used. A machine shop's carbon footprint can be determined with this work if its electricity source is known. Carbon emissions from industry can be lowered by switching to more energy-efficient production methods.

Keywords: Energy consumption, turning process, workpiece, materials (titanium alloys), optimal tool life, cutting, machinability, CNC lathe

INTRODUCTION

The most sustainable manufacturing solutions have never been more critical to reduce the environmental impact of industrial operations due to recent global developments. However, energy usage is one of the most important performance indicators for evaluating an enterprise's environmental credentials. Energy consumption can be used to determine the carbon emission penalty (amount of high-resolution when producing the energy). The mechanics of machining have gained much attention in research and development since it continues to be one of the most important discrete pieces in manufacturing processes [1–2]. On the other hand, the energy analysis of machining processes is a relatively young field. This chapter analyses energy consumption to determine how machine usage affects the environment. It takes into account the energy needs when cutting a variety of alloys under advised cutting circumstances. The energy was made accessible by the need for electrical power in the machining process. The findings show how high-speed machining may affect energy usage and, as a result, a more sustainable machining sector [3]. According to the

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research that was conducted, the amount of energy necessary for the operations of material removal may be relatively low when compared to the overall amount of energy necessary for the operation of the machine tool [4]. Primary processes in material production have a higher energy footprint than secondary shaping. [5]. Because of this, doing a life-cycle study of products before determining their energy footprint is essential. The consumer often determines the raw material inputs for manufacturing firms despite the existence of this element. Thus, sustainable innovations aim to enhance subsequent stages of manufacturing. According to the research that has been conducted, issues pertaining to the economy, the environment, and society should serve as the three pillars around which sustainable development should be built [6-7]. Creating environmentally friendly goods should be a priority for businesses [8] if we are to achieve sustainable development. One of the ways to create ecologically sustainable products is to cut down on the amount of energy used in both the manufacturing process and the use of the products. The more energy consumption there is, the higher the manufacturing costs and carbon dioxide emissions ($C0_2$) [9].

How energy affects how different types of workpiece materials are machined

How milling machines use energy gave the researchers ideas for their work. However, the research discussed in this chapter was carried out with a CNC lathe and concentrated on how much energy is required to process various types of workpiece materials [10]. An examination was carried out on both the power consumption of a lathe machining center in standby mode and power consumption when cutting particular industrial alloys and when the spindle is turned off. [11–12]. A general-purpose TiN-coated CNMG 120 carbide insert was utilized to standardize the cutting experiments and allow for comparisons between the various materials. This was fastened on a magnetic tool holder. Both the feed rate, which was set to 0.20 millimeters per revolution, and the depth of cut, which was set to 1.4 millimeters, fell within the range of values recommended for the workpiece's materials. To arrive at an accurate conclusion, we compared the power and, by extension, the energy needed to cut each material type under ideal conditions [13–15].

LITERATURE REVIEW

Ref.	Insights	Results	Methods used	Contributions
[16]	Turning processes affect sustainability due to their energy consumption. Optimizing cutting parameters can decrease energy consumption.	Time of total processing: 4.953 minutes Energy consumption in total: 5,434 MJ	MOORA is an approach to multi-objective optimization based on ratio analysis.	The development of an optimization model for a multi-pass turning procedure
[17]	Machining environment that impacts energy consumption. Vortex tube cooling increases energy usage and impacts power and surface quality.	An effective cooling method utilizing vortex tubes reduced surface irregularity by 31.4%.	Response surface method mathematical models	Impact of Machining Environment Variations on energy and surface roughness Analysis
[18]	Turn-mill manufacturing should prioritize energy efficiency.	Accuracy of 95% in energy consumption estimation.	Generic energy model development for turn-mill machine tools	Verification and development of a generic energy model
[19]	Productivity-driven energy consumption analysis of rotating processes.	-	Model of experimental-mathematical regression for the analysis of cutting force	Methods of optimization proposed to conserve energy.
[20]	Prioritise exergy analysis and turning efficiency when working with DIN 1.2367 material.	-	Turning process exergy analysis and efficiency calculation	Increased energy efficiency by emphasizing the value of exergy analysis

[21]	Increased energy efficiency by emphasizing the value of exergy analysis.	The model exhibits the most minor mean relative error.	Using PSO-SVM for forecasting	An innovative model was devised to forecast surface irregularity by leveraging energy consumption data.
[22]	A detailed analysis of the cutting energy and power.	The feed rate and cutting speed considerably affect energy consumption and cutting power.	DOE, ANOVA, Taguchi,	Energy efficiency optimization in machining was the subject of the insights provided.
[23]	Comprehensive examination of the energy usage of a two-spindle turning center.	Energy consumption reduction strategies are recommended.	-	Strategies for energy conservation in machine tools were presented.
[24]	The effect of cutting speed on specific cutting energy is analyzed.	-	A comparison between theoretical calculations and simulation results from Autodesk Software	An exhaustive comparison of the effects of cutting speed on energy consumption was presented.
[25]	Developing mathematical models to forecast the parameters of the machining process and the durability of tools.	The numerical simulation outcomes pertaining to the fluctuations in cutting force and contact temperatures.	Modelling by finite elements and mathematics	A comprehensive comprehension of the manner in which material properties influence the temperature field during turning
[26]	Experiments involving turning two distinct CFRP composites determine the precise cutting energy.	The specific cutting energy increases exponentially with decreasing feed rates.	Critical energy and power constants are assessed.	Examined the effect of machining conditions on CFRP machining energy consumption
[27]	The optimization of turning process parameters for GFRP through the application of Grey Relational Analysis (GRA) and ANOVA.	Identification of the optimal parametric combination.	Analysis of Variance (ANOVA), Grey Relational Analysis (GRA),	Optimization of turning process parameters in GFRP composites to increase material removal rate and surface roughness
[28]	Innovative technique for enhancing the quality of polymer components by integrating chemical and mechanical processing.	Treatment-induced reduction in roughness parameters by a factor of 2-4.5.	A method combining chemical treatment	A novel technique for improving the quality of turned polymer components was introduced.

Analysis of Different Energy Constants

To determine the specific cutting energy, k, for each material, 9 different cutting speeds were used. Tables 1 to 5 detail each material's cutting speeds and specifications. The cutting tests resulted in a graph of machining power versus material removal rate at varying cutting speeds. Results for all of the workpiece materials are displayed in Figure 1. Table 6 displays the results of evaluating the specific energy of several materials. These numbers indicate how easily a material can be machined, considering both the tool life required and the quality of the finished product.

Table 1. Optimal cutting conditions for Aluminium

Cutting speed (V_C) (mm/min)	Length of cut(l mm)	Axial depth of cut (A_p)(mm)	Feed rate(mm/rev)	Initial diameter (D_i)[mm]	Final diameter (D_f)[mm]	Material removal rate (mm^3/s)	Power for machining (P_{net})[W]
200	120	1.4	0.20	80.2	77.9	425	952
225	120	1.4	0.20	76.3	74.4	582	1432

250	120	1.4	0.20	72.1	70.1	610	1692
275	120	1.4	0.20	69.4	66.2	683	2010
300	120	1.4	0.20	65.8	62.4	772	2145
325	120	1.4	0.20	61.2	58.6	836	2321
350	120	1.4	0.20	57.7	54.9	895	954
375	120	1.4	0.20	53.5	51.4	931	1136
400	120	1.4	0.20	50.2	48.8	990	1021

Table 2. Optimal cutting conditions for Cast iron

Cutting speed(V_C) (mm/min)	**Length of cut (l mm)**	**Axial depth of cut (A_p)(mm)**	**Feed rate (mm/rev)**	**(D_i) [mm]**	**(D_f) [mm]**	**Material removal rate (mm^3/s)**	**Power for machining (P_{net})[W]**
200	120	1.4	0.20	42.1	38.5	310	2241
225	120	1.4	0.20	37.5	34.3	360	2123
250	120	1.4	0.20	34.3	30.8	390	2236
275	120	1.4	0.20	30.8	27.1	441	2014
300	120	1.4	0.20	26.7	24.6	477	2110
325	120	1.4	0.20	23.4	20.8	501	2345
350	120	1.4	0.20	20.2	18.2	521	2265
375	120	1.4	0.20	17.4	15.7	547	2101
400	120	1.4	0.20	14.5	13.8	561	2154

Table 3. Optimal cutting conditions for steel

Cutting speed (V_C)(mm/min)	**Length of cut (l mm)**	**Axial depth of cut (A_p) (mm)**	**Feed rate (mm/rev)**	**(D_i) [mm]**	**(D_f) [mm]**	**Material removal rate(mm^3/s)**	**Power for machining (P_{net})[W]**
200	120	1.4	0.20	64.2	61.8	462	2123
225	120	1.4	0.20	59.4	56.2	538	2425
250	120	1.4	0.20	55.5	52.4	595	2592
275	120	1.4	0.20	51.7	49.3	648	2725
300	120	1.4	0.20	48.4	44.1	709	3474
325	120	1.4	0.20	45.5	41.4	795	4036
350	120	1.4	0.20	41.8	38.5	865	3452
375	120	1.4	0.20	39.4	36.9	915	3202
400	120	1.4	0.20	36.1	34.2	990	2995

Table 4. Cutting parameters for brass

Cutting speed (V_C) (mm/min)	**Length of cut (l mm)**	**Axial depth of cut (A_p)(mm)**	**Feed rate (mm/rev)**	**(D_i)[mm]**	**(D_f)[mm]**	**Material removal rate(mm^3/s)**	**Power for machining (P_{net}) [W]**
120	80	1.4	0.20	35.3	33.0	301	1260
130	80	1.4	0.20	32.2	30.4	342	1269
140	80	1.4	0.20	28.3	26.7	385	1102
150	80	1.4	0.20	28.5	24.1	423	1249
160	80	1.4	0.20	24.6	20.9	462	1388
170	80	1.4	0.20	21.3	22.7	512	1485
180	80	1.4	0.20	19.2	18.5	560	1352
190	80	1.4	0.20	17.1	15.8	598	1215
200	80	1.4	0.20	15.6	13.2	634	1354

Table 5. Titanium alloy cutting parameters

Cutting speed (V_C) (mm/min)	Length of cut (l mm)	Axial depth of cut (A_p)(mm)	Feed rate (mm/rev)	(D_i)[mm]	(D_f)[mm]	Material removal rate(mm^3/s)	Power for machining (P_{net})[W]
60	120	1.4	0.20	82.3	79.4	188	2652
80	120	1.4	0.20	78.1	75.5	231	2752
100	120	1.4	0.20	75.5	72.3	292	2967
120	120	1.4	0.20	71.7	68.2	340	3105
140	120	1.4	0.20	67.3	63.7	400	3236
160	120	1.4	0.20	63.9	59.2	464	3378
180	120	1.4	0.20	59.7	56.3	499	3374
200	120	1.4	0.20	55.4	53.5	572	3398
220	120	1.4	0.20	54.2	51.5	624	3324

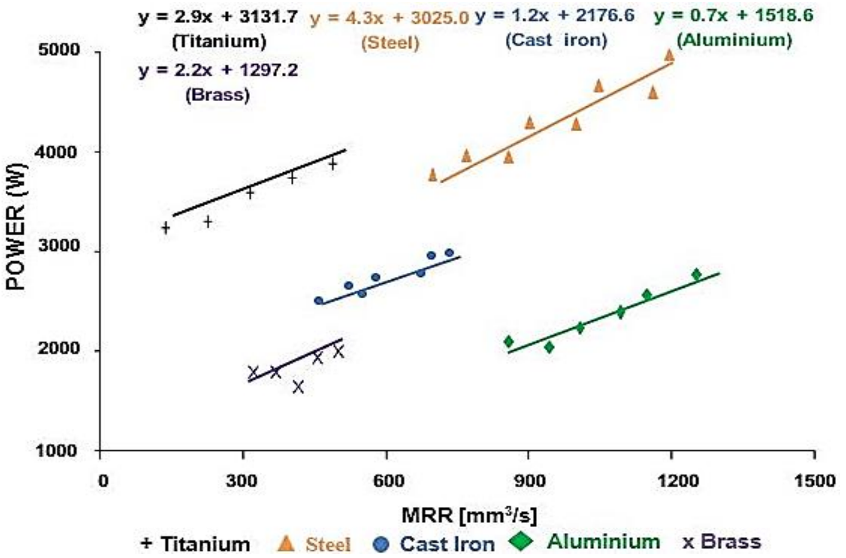


Figure1. The effects of the material reduction rate (MRR) on energy consumption

Table 6. Evaluation of cutting tests' specific power requirement

Material of workpiece	Specific cutting energy k[Ws/mm3]
Titanium alloy	3.05
Brass	2.3
Cast iron	1.8
Aluminium	0.9
Steel	4.5

The data in Table 6 validate the techniques employed here to evaluate the individual energy requirements for cutting operations because they fall within the specified range of requirements (Table 7).

Table 7. Various materials require different amounts of cutting energy.

Material	Specific cutting energy, k [Ws/mm^3]
High-temperature alloys	3.2 – 8
Titanium alloys	2 – 5
Steels	2 – 9
Stainless steels	2 – 5

Nickel alloys	4.8 – 6.7
Cast irons	1.1 – 5.4
Aluminium alloy	0.4 – 1
Refractory alloys	3 – 9
Copper alloys	1.4 – 3.2
Magnesium alloys	0.3 – 0.6

The experimentation examined the energy and power needs for the machining process for each of the several types of materials. In day-to-day business, many machine shops base their decisions on the recommendations available by the tool vendors they work with. As a result, this analysis sheds information on the relative energy requirements associated with industrial machining procedures. Utilizing distinct cutting tools and tool geometries is a potential source of deviations from the results described here. On the other hand, carbide-cutting tools are the most adaptable in their application across a broad spectrum of cutting speeds. As a result, they provide the best alternative for comparative research because of their vast range of applications. In addition to that, the majority of these instruments are now covered.

Specific Cutting energy

The Table 8 shows the individual cutting energy (k) values for the following materials: steel, brass, aluminium, titanium alloy, cast iron, and steel, for a range of cutting speeds from 200 mm/min to 400 mm/min. With a slight peak at 275 mm/min, aluminium exhibits a general trend of decreasing specific cutting energy as cutting speed increases, starting at 2.240 W/mm³/s at 200 mm/min and decreasing to 1.031 W/mm³/s at 400 mm/min. Specific cutting energy for cast iron decreases steadily with increasing cutting speed; it starts at 7.228 W/mm³/s and drops off quickly to 3.839 W/mm³/s at 400 mm/min. The pattern for steel is more variable; it starts at 4.596 W/mm³/s, dips in the middle, increases marginally at 325 mm/min to 5.076 W/mm³/s, and then drops once more to 3.025 W/mm³/s at 400 mm/min. Similar to some other materials, brass also exhibits a decreasing trend as speed increases, falling from 4.185 W/mm³/s to 2.136 W/mm³/s, though this decrease is not as linear. Titanium Alloy has the highest specific cutting energy at first, 14.106 W/mm³/s, but as speed increases, it consistently decreases, reaching 5.327 W/mm³/s. All materials benefit from higher cutting speeds in terms of lower energy consumption per unit volume of material removed, according to the data, though the rate of improvement and the starting points differ greatly between materials. Despite having a high initial energy requirement, titanium alloy exhibits the largest decrease, demonstrating how responsive it is to higher cutting speeds in terms of energy efficiency shown in figure 2. To maximise cutting conditions and comprehend machining efficiency, the analysis of specific cutting energy is essential. Reduced specific energy values signify enhanced efficiency, implying a lower power requirement for the removal of a unit volume of material. Although harder materials like titanium alloy improve significantly with speed, they start with a much higher base energy requirement. In contrast, materials like brass and aluminium tend to be more efficient to machine at higher speeds.

Table 8. Specific Cutting Energy For Aluminium, Cast Iron, Steel, Brass Titanium Alloy

Cutting Speed (VC) (mm/min)	**Specific Cutting Energy (k) (W/mm³/s) Aluminium**	**Specific Cutting Energy (k) (W/mm³/s) Cast Iron**	**Specific Cutting Energy (k) (W/mm³/s) Steel**	**Cutting Speed (VC) (mm/min)**	**Specific Cutting Energy (k) (W/mm³/s) Brass**	**Cutting Speed (VC) (mm/min)**	**Specific Cutting Energy (k) (W/mm³/s) Titanium alloy**
200	2.240	7.228	4.596	120	4.185	60	14.106
225	2.460	5.897	4.507	130	3.710	80	11.913
250	2.774	5.733	4.356	140	2.862	100	10.161
275	2.943	4.566	4.205	150	2.953	120	9.132
300	2.778	4.425	4.899	160	3.004	140	8.090
325	2.776	4.679	5.076	170	2.900	160	7.280

350	1.066	4.347	3.991	180	2.414	180	6.762
375	1.220	3.841	3.499	190	2.032	200	5.941
400	1.031	3.839	3.025	200	2.136	220	5.327

RESULTS AND DISCUSSION

Figure 3 illustrates, as a percentage, the proportionate amount of power that a machining center requires. It is shown in figure 3 (a to e) that the machining operation only uses between 13% and 36% of the total power drawn during the procedure. Most of the available electricity was consumed by activities that did not involve cutting. The spindle, control computer, and cooling fans consume most of the energy necessary for the machine to function effectively. This is presumably a characteristic of turning machines in which the spindle is constructed or selected to generate sufficient force to rotate the workpiece. One of the problems that engineers need to work on is perfecting the design process to make their products more useful and have fewer adverse effects on the environment. The provision of the coolant in this machine takes between 4% and 9% of the power required; hence, this amount of electricity and energy can be conserved by switching to dry machining. This study found that 38%, 31%, 28%, 31%, 13%, and of power were required to cut. The non-cutting operation power was the most critical factor in the machining process across all tests. However, the amount of power or energy a machine tool uses is rarely considered a priority for optimization while it is being designed.

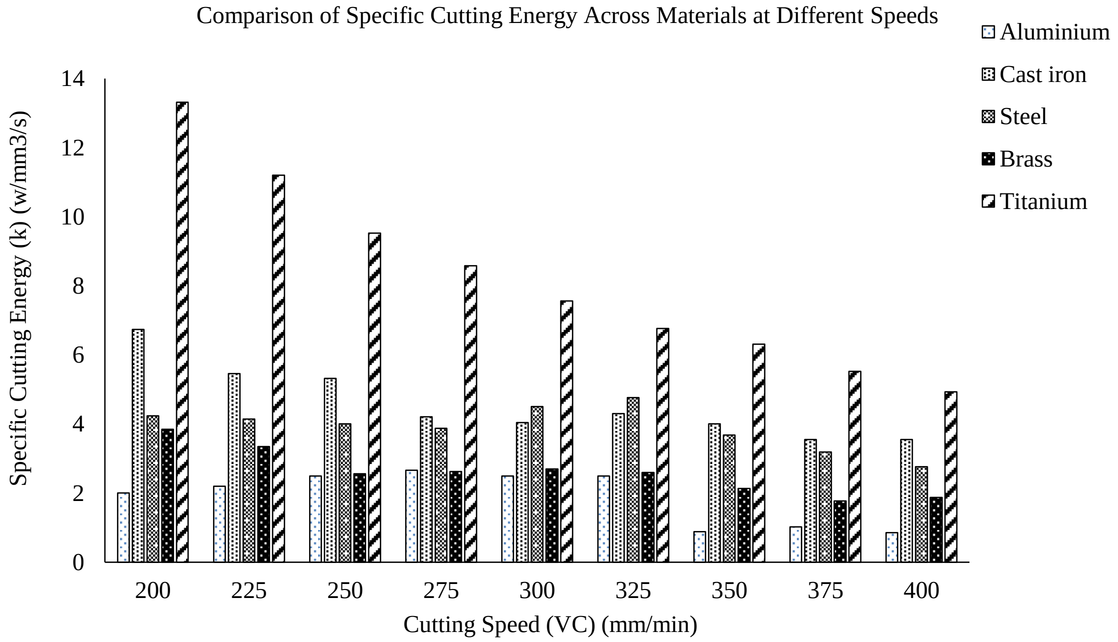
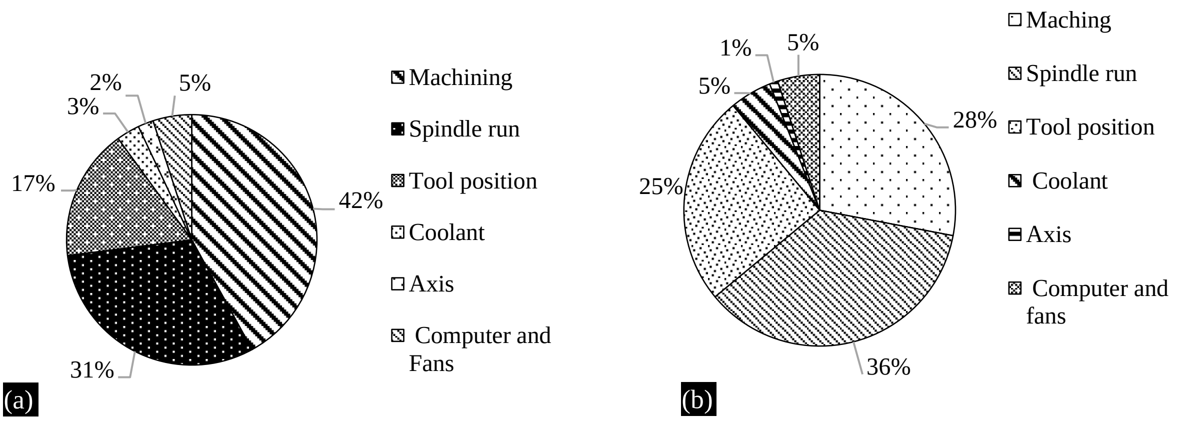


Figure 2. Comparision of specific cutting energy



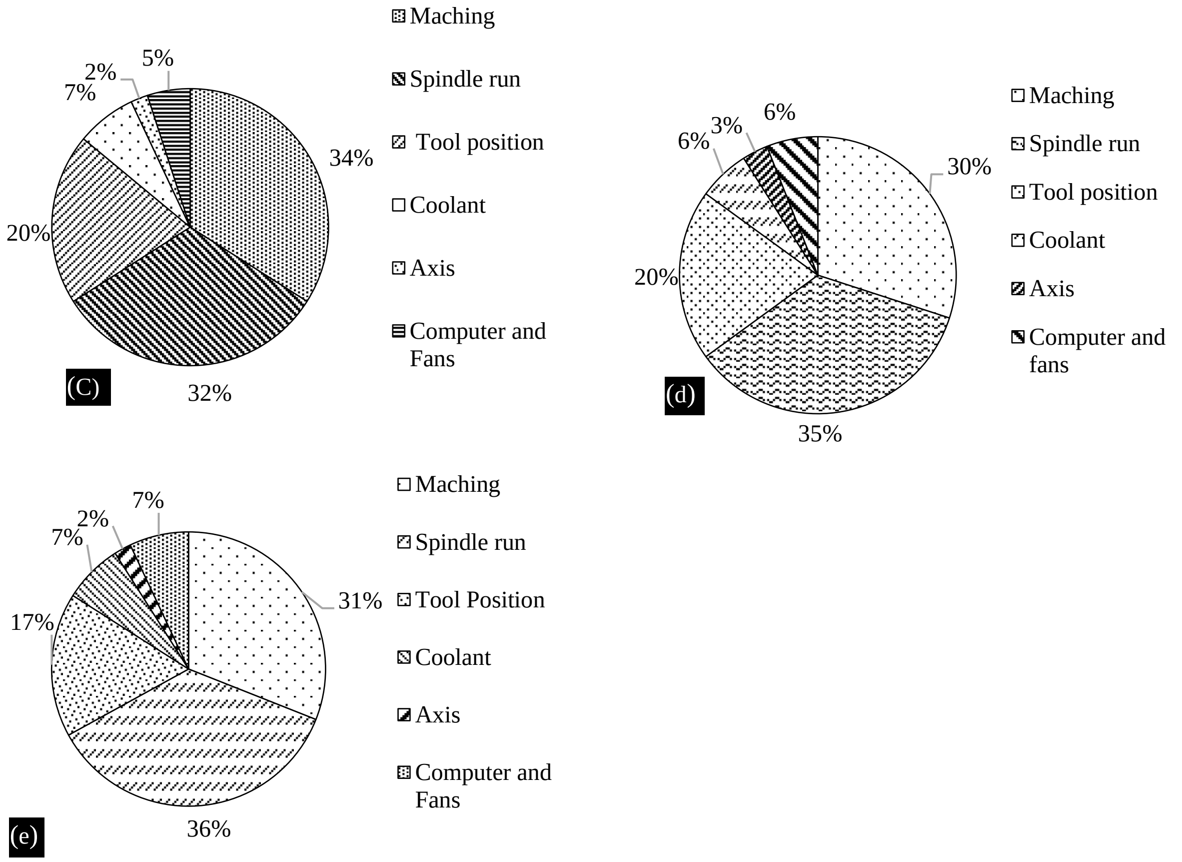


Figure 3. For the purpose of cutting various workpiece materials, the MHP lathe's power distribution: (a) Al alloy, (b) CI (Cast iron), (c) EN 8 steel, (d) Brass, (e) Titanium alloy

The amount of energy needed to excavate 10 cm^3 of material was considered. By increasing the required power by the material removal rate, the amount of time needed to machine it was calculated. Finishing cutting settings for turning operations were derived from the cutting parameters specified by the tool supplier and displayed in Table 9.

Table 9. Cutting parameters adapted

Parameters	Cast iron	Titanium alloy	Aluminium	Steel	Brass
Feed rate (mm/rev)	0.30	0.15	654	0.25	0.15
Cutting speed (mm/min)	240	75	1.50	395	140
Depth of cut (mm)	0.30	0.15	0.30	0.25	0.15

Figure 3 demonstrates that titanium alloy requires a much higher total energy to remove 10 cm3 than other materials. Titanium, in particular, required the slowest machining speeds and material removal rates of all these alloys. Therefore, low volumetric rate machining operations require more time for the cutter to remove a given amount of material. The increased energy use was, therefore, a cost of doing this. One obvious advantage of high-speed or rapid machining is a decreased need for power to produce the final product. Machining an aluminum alloy at its maximum cutting speed resulted in the lowest energy footprint possible. However, while aluminum has the fastest cutting speed of the materials considered, it does not always require the most energy to remove the same volume of material. Figure 3 illustrates how the total amount of energy used for machining changes significantly depending on the material being processed. Figures 4 and 5 show that the non-cutting procedures account for most of the energy used during machining.

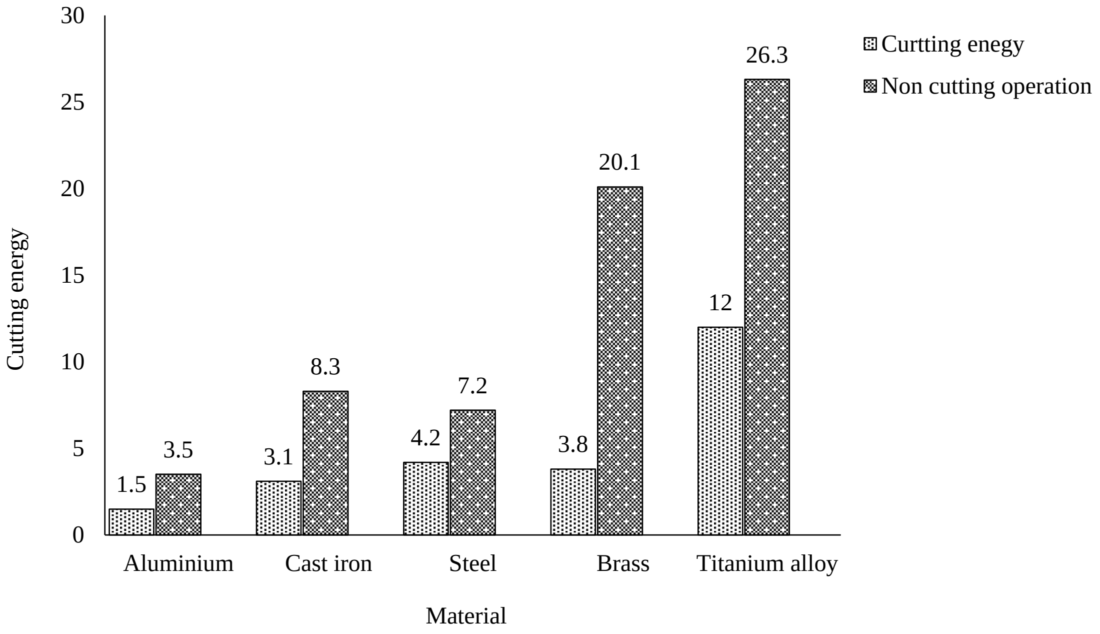


Figure 4. Overall energy needed to remove the material

These numbers are based on the feed rate used to machine the materials. Brass has a slower feed rate, 0.20 mm/rev than steel and cast iron. That's why it takes longer to machine 10 mm^3 of brass than steel or cast iron. Slower material removal rates and higher energy demands are inevitable consequences. As indicated, increasing productivity can reduce the amount of energy used during machining (i.e., MRR rates). We wouldn't produce as much carbon dioxide if we all used less energy. For sustainable production, cutting down on carbon emissions is crucial. Figure 4 displays the estimated quantity of carbon emissions from waste disposal of 10 mm^3, highlighting this advantage. Ten times as much carbon is released when milling 10 mm^3 of titanium alloy as when milling the same aluminum alloy volume.

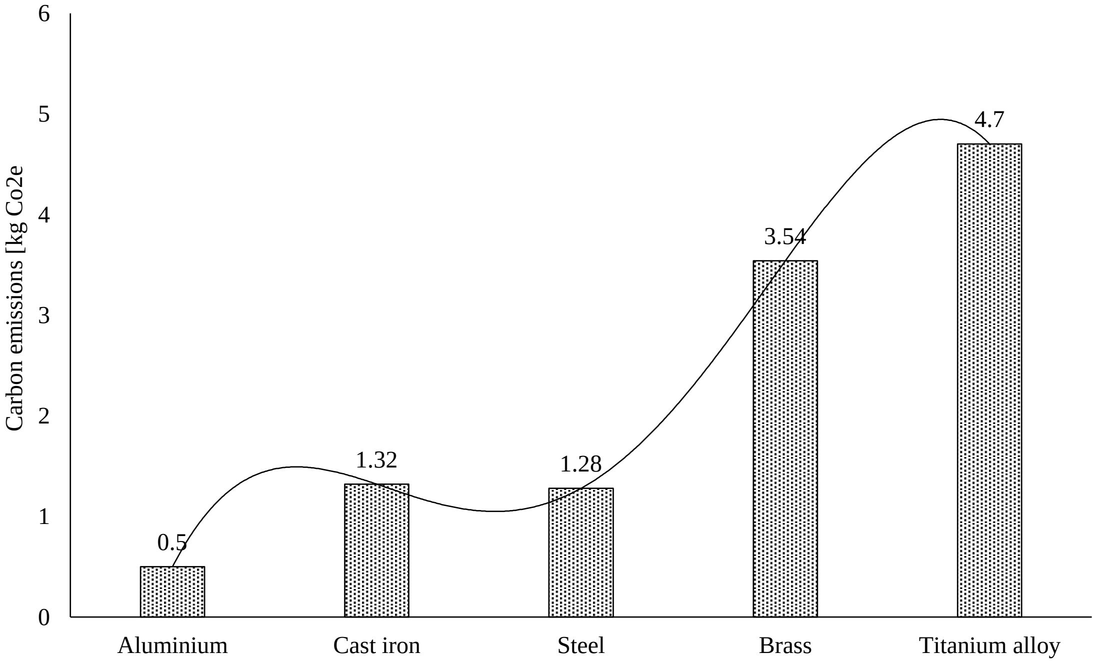


Figure 5. Carbon emissions in removal from the material.

Meanwhile, the carbon emissions from cast iron and steel are essentially the same. Brass has a larger carbon emission than aluminium, cast iron, and steel because of the lower feed rate, which leads to longer machining times. It stands to reason that longer machining times would increase energy use and, by extension, higher carbon emissions. The high carbon emission alarmingly indicates the impact of using various materials in machining processes. Due to many constraints, including the qualities of the selected material and the cost of manufacture, this indicator was generally overlooked until today. Efforts must be made to address this issue and promote environmentally responsible production methods. The above analysis elucidates material choice has influence on power consumption, energy consumption, and carbon emissions.

CONCLUSION

In the case of energy-intensive procedures, such as machining, the energy consumed during the process approximates the carbon footprint derived from that energy. This is a result of the carbon dioxide emissions generated in the process of generating the electricity utilized to operate the machinery. Due to the available energy and the imperative to reduce the environmental impact of human activity, it is critical to increase production efficiency. An examination of a CNC lathe's power and energy consumption demonstrates that non-cutting operations consume most of the device's power. Depending on the workpiece material, It was discovered that only 12% to 30% of the total energy needed in a machining operation was used for cutting. This was the case with numerous workpiece materials. By purposefully designing machines with a minimal energy footprint, it is possible to increase the long-term viability of machining operations. It was found that the spindle of the lathe was the biggest consumer of electricity. Conversely, cutting without the use of coolants can reduce energy and power consumption by at least 4%

Dry machining can yield substantial cost savings compared to wet machining, as the machine's coolant system consumes merely 4–9 percent of the overall energy consumed. The minimum power required to cut aluminum, cast iron, steel, brass, and titanium alloy, according to this study, was 28%, 31%, 38%, 13%, and 31%, respectively. The study findings indicated that reducing energy consumption was possible by either increasing the machining speed or the volumetric removal rate, consistent with the product's removal volume. Additionally, the energy required is affected by the material being machined. Including the machine shop's power supply information could expand the scope of this undertaking, enabling a more accurate estimation of the associated costs.

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